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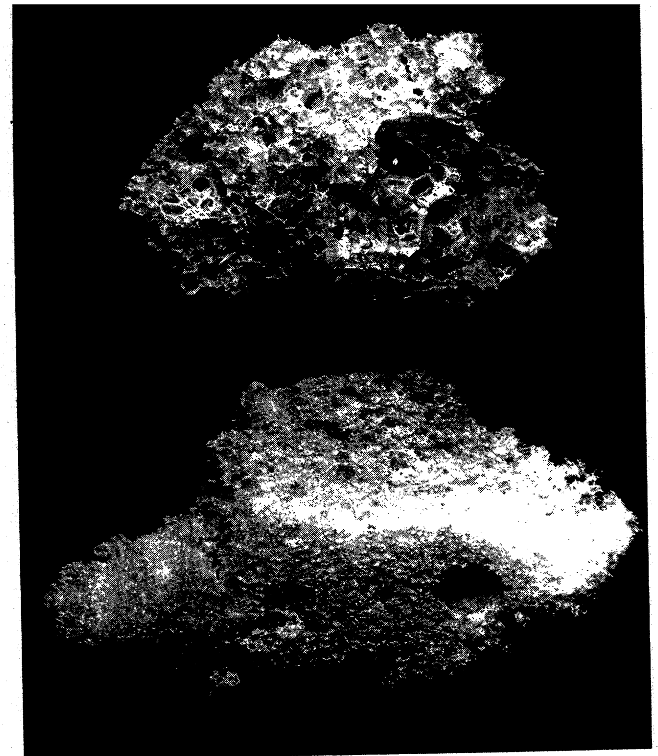

Fig. 1—**STRUCTURES** *of vacuum foam-dried milk particles obtained by water vapor (top) and entrained gas of low solubility (bottom)*

from Concept through Market Testing

THE *development* OF VACUUM FOAM-DRIED WHOLE MILK

H. I. SINNAMON, N. C. ACETO and E. F. SCHOPPET

□ DRY WHOLE MILK has been traced back before the time of Marco Polo (Coulter and Jenness, 1964) who reported that it had been used by the soldiers of Genghis Khan as part of their ration (Hunziker, 1949). Widespread interest in this product, however, probably began in the nineteenth century. According to the technical and patent literature, during almost the whole of that century efforts were made to produce a good dry whole milk.

The degree of success of these ventures can be inferred from the comment of Fleischmann, a noted German dairy scientist of the day, who indicated in 1901 that it would not be possible to produce a marketable dry whole milk worthy of the name (Hunziker, 1949). In spite of Dr. Fleischmann's discouraging pronouncement, work has continued on the problem to this day. Apparently there is a need for a good dry whole milk.

PROBLEMS IN DRYING WHOLE MILK

Most dry milk today is manufactured either by spray drying or by roller drying. Spray drying is the more important of the two (Bullock, 1962). Various modifications of this method have been developed since World War II that have led to "instant" dispersibility

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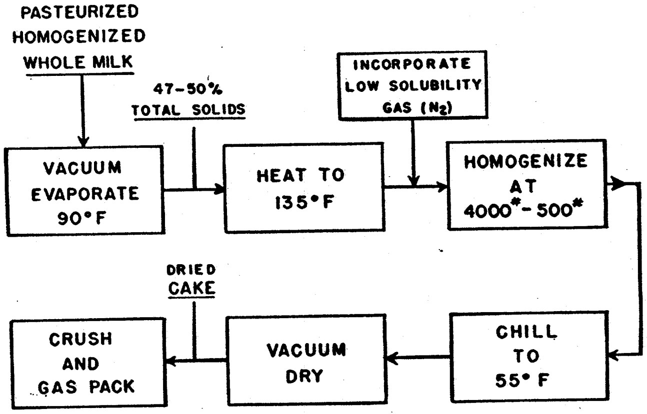

Fig. 2—**BATCH PROCESS** *flow diagram*

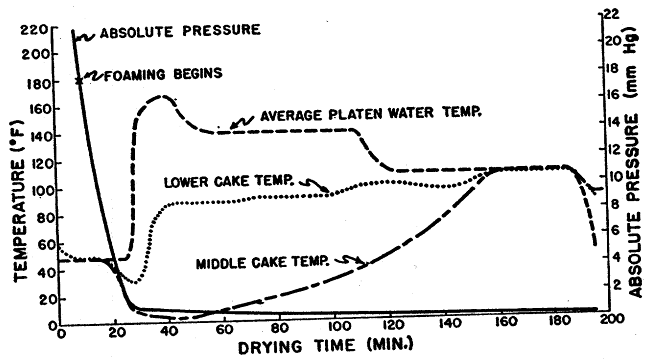

Fig. 3—**DRYING CYCLE** *for vacuum foam-drying of whole milk in a vacuum shelf dryer*

for dry skim milk, and as a result dry skim milk has become a successful product of commerce. These instantizing techniques, however, have not been suited to dry whole milk (King, 1966).

From a flavor standpoint, too, major problems arise when drying whole milk that are absent in the case of skim. Dry whole milk of the recent past has been described as very difficult to disperse (particularly without using warm water), inclined to taste highly cooked and "eggy," and deteriorating during storage to flavors such as tallowy, rancid, stale, burnt feathers, etc. (Mook and Williams, 1966). This was the state of the art when the present work was begun. The objective of the research was to develop a commercially feasible process for the preparation of a beverage-quality dry whole milk that would disperse easily in cold water, have the flavor of fresh whole milk when newly prepared, and maintain those properties for a reasonable time in storage.

DEVELOPING THE BATCH PROCESS

In view of the poor quality of the dry whole milks available when this work began, the first problem seemed to be to determine if it even would be possible to produce a dry whole milk of the desired good flavor and easy dispersibility. In the usual drying practice fresh flavor was sacrificed by "forewarming" the milk under heating conditions much more rigorous than simple pasteurization. "Forewarming" was presumably necessary because it either produced natural antioxidants which were needed to combat fat oxidation during spray drying and storage, or because it destroyed the oxidizing enzymes present in milk (Hunziker, 1949), but the treatment also imparted a cooked flavor to the milk. To adopt forewarming would be to compromise the objective of the work. It was therefore decided to eliminate it if possible.

Another obvious way to avoid oxidation during drying was to dry under vacuum. Vacuum drying also appeared to offer rapid dispersibility through "puff-drying"—a technique in which a highly expanded, sponge-like structure is created by water vapor bubbles as they form in a liquid concentrate during vacuum drying. Puff-drying had produced dry fruit juices that dissolve rapidly in water (Strashun and Talburt, 1953). For these reasons puff-drying techniques were employed in the first attempts to produce a satisfactory dry whole milk. These experiments were carried out batch-wise in a vacuum shelf dryer.

PRODUCT STRUCTURE & DISPERSIBILITY

Puffed structures can be developed by various devices, and for materials which are readily soluble the type of structure may not be of prime importance for rapid dispersibility. With whole milk, however, the structure was found to markedly influence the dispersibility rate of the dried product. Two possible structures are illustrated in Figure 1. The puffed form on the top was developed during vacuum drying by the evolution of water vapor from a degassed concentrate. This is characterized by large, nonuniform bubbles and a heavy, tough, intercellular structure. Product obtained from such a form disperses very poorly compared to that shown on the bottom. The latter was formed by the expansion of entrained gas of low solubility (nitrogen) in the concentrated milk as the pressure in the dryer was reduced. This form is characterized by small, uniform bubbles and a fine, fragile, intercellular structure. It is the latter—the desirable form—which was called "foam" (Sinnamon et al., 1957).

It was further found that the mere use of an entrained gas does not insure a form that will disperse readily. In order for entrained gas to be effective in forming a fine-grained foam as pressure is reduced, the concentrate must be held at a low enough temperature to allow the entrained gas to expand sufficiently in situ to form the foam before the pressure in the dryer reaches the flash point of the concentrate. If the flash point is reached first, the concentrate will boil, removing the entrained gas. The resulting structure will then be the form caused by bubbles of water vapor in a degassed concentrate (Sinnamon et al., 1957).

DETAILS OF THE BATCH PROCESS

The flow diagram for the batch process as finally developed is given in Figure 2. Fresh pasteurized, homogenized milk is concentrated to about 48% solids content at a temperature of 90°F in a high vacuum, falling-film evaporator. It is then heated to 135°F and homogenized—first at 4000 psi and then at 500

DEVELOPMENT of vacuum foam-dried whole-milk

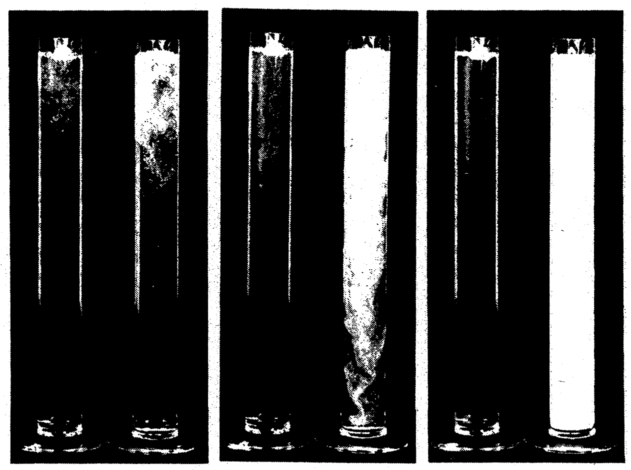

Fig. 4—**SELF-DISPERSIBILITY** *in cold water of vacuum foam-dried milk (sample at right) is compared with that of spray-dried whole milk (sample at left)*

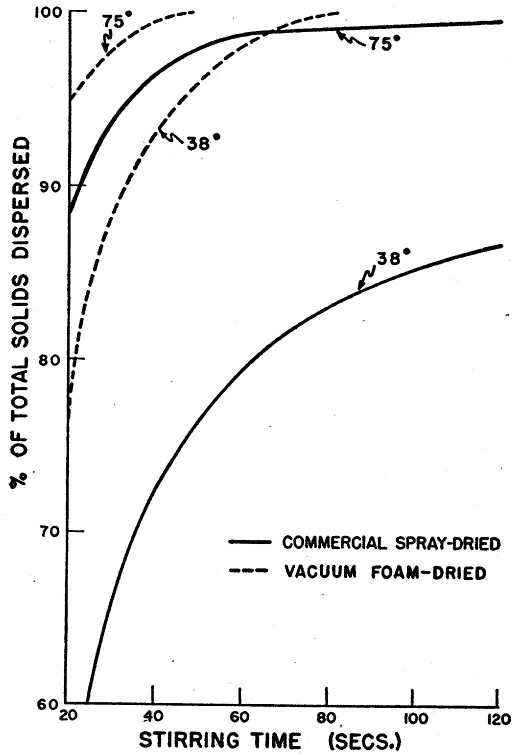

Fig. 5—**DISPERSIBILITY RATES** *for vacuum foam-dried and commercial spray-dried whole milks*

psi—in a single-stage homogenizer of the pulsator type. Immediately prior to homogenization nitrogen is bubbled through the concentrate from a fritted glass sparger, dispersing entrained gas through the material. The concentrated milk is then flowed over stainless steel drying pans to an average depth of 1/16 in, chilled to 55°F or below, and dried as a foam in a vacuum shelf dryer. The resulting dried mass is crushed lightly through stainless steel screens.

The drying cycle in the shelf dryer is shown in Figure 3. It can be seen here that drying proper (indicated by the sudden decrease in temperature of the cake of milk foam) does not begin until well after foaming has begun. Thus, in vacuum foam-drying two separate phenomena occur sequentially under vacuum. In the first the foam is created and in the second the foam is dried. In puff-drying, on the other hand, the puff is formed during and as a result of the drying proper.

INITIAL PRODUCT PROPERTIES

The product that resulted from vacuum foam-drying met the requirements of the objective for initial flavor and dispersibility and was therefore tested extensively. In dispersibility, Figure 4 shows how the new product dispersed when placed on the surface of water as compared to a spray dried product. Figure 5 shows how the two products compared when a quantitative dispersibility test was applied to them (Sinnamon et al., 1957). It was found that screening the foam through 20-mesh resulted in more rapid dispersing but a more bulky product than screening through 40-mesh (Sinnamon et al., 1957).

STORAGE STABILITY

Results of storage studies showed that dispersibility of the product was unimpaired after a year's storage at 73°F, but deteriorated at 100°F (Eskew et al., 1958); and that "forewarming" resulted in a more rapid loss of dispersibility during storage at 100°F with no apparent improvement in flavor stability (Eskew et al., 1958).

Storage studies also showed that with oxygen present in the container at 73°F the product stored best if its moisture content was between about 2.8% and 5.1%, and that the moisture content corresponding to a Brunauer-Emett-Teller monolayer was 3.95% (Aceto et al., 1965). Very important findings for the future work were that the 5-hydroxymethylfurfural content of the freshly-dried product could be used both as a measure of the heat treatment undergone during processing, and as an indicator of the future storage stability of the product (Craig et al., 1961). These findings were later found to be so important that research was carried out on the method of analysis (Della Monica et al., 1968b).

TRANSLATION TO THE CONTINUOUS PROCESS

The product aspect of the objective was satisfied by the development of the vacuum foam-drying process. Attention was now turned to the requirement of commercial feasibility. An economic analysis showed that the batch process was too costly (Claffey, J.B., personal communication) to be of commercial significance, so an integrated pilot plant was designed and built for the translation of the batch process to a con-

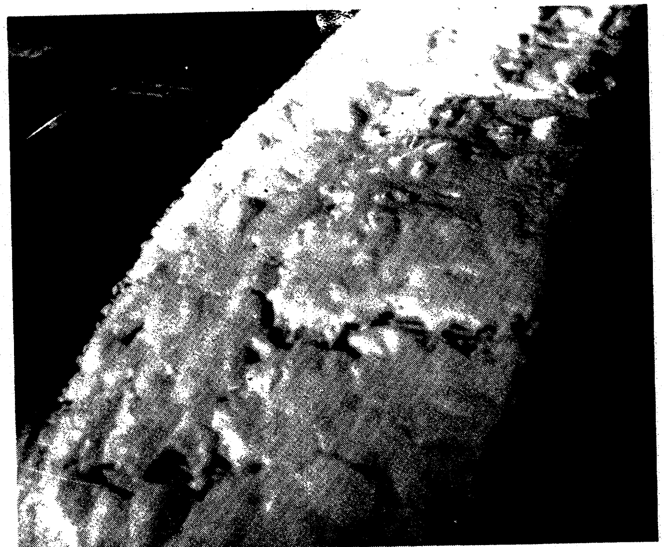

Fig. 6—**STABLE FOAM** *being dried at a drying chamber pressure of 3mm Hg*

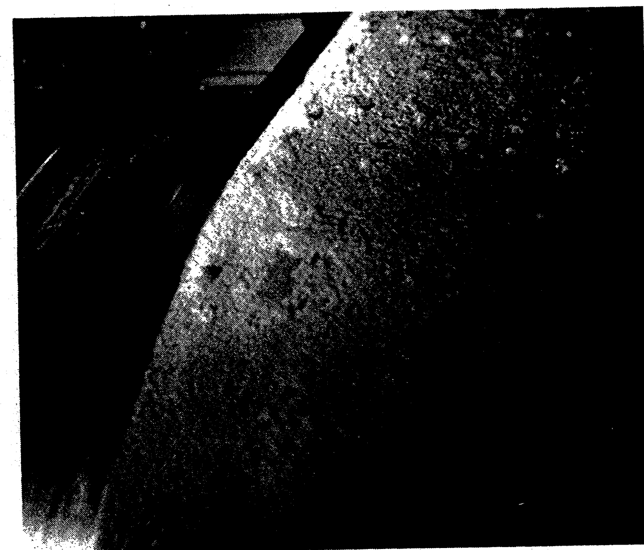

Fig. 7—**SEMI-STABLE FOAM** *being dried at a drying chamber pressure of 19mm Hg*

tinuous one (Aceto et al., 1962).

Raw whole milk is adjusted to 26% fat content, pasteurized and homogenized according to accepted practice. This milk is then concentrated in a single-pass, agitated falling-film vacuum evaporator to a constant apparent viscosity. The milk is introduced at the top of the evaporating section and flows down the inside wall of the evaporator body while steam for evaporation is maintained on the outside wall. Four blades of a rotor turning inside the body and clearing the inside wall by 1/32 in spread the milk into a thin, turbulent film across the whole inside wall of the evaporator, thus providing highly efficient conditions for evaporation. In a descent of only 23 in, the milk is evaporated at a high rate from 12% to 45% solids content. Viscosity is the control variable because it is a prime factor contributing to the formation and stability of fluid foams, and because in milk concentrates viscosity and solids content do not correlate well from one batch to another.

The concentrate is homogenized in a two-stage, single-pass, variable rate homogenizer operating at 3000 and 500 psi. The function of the second homogenization is to eliminate "oiling off" of the reconstituted milk. This treatment also reduces substantially all of the fat particles to below 2μ in diameter. The homogenizer also acts as a pump that fixes the concentrate flow rate for gas dispersion. Nitrogen is metered into the concentrate stream just ahead of two scraped surface heat exchangers that simultaneously chill the concentrate to about 35°F and disperse the nitrogen to a bubble size of less than 75μ. The gas-containing concentrate is then delivered to the dryer through a metering pump.

The key piece of equipment in the pilot plant is the continuous vacuum dehydrator. This dryer consists of an endless solid stainless steel belt 12 in wide which alternately passes over heating and cooling drums. The drums are 2 ft in diameter and are spaced 9 ft between centers. Either vacuum or pressure steam can be supplied to the heating drum, and coolant at various temperatures can be circulated through the cooling drum. Heat can be applied to either side of the belt between the two drums by means of banks of individually controlled electrical radiant heaters. The whole apparatus is enclosed in a chamber where pressures can be maintained from 50 to 0.5 mm Hg absolute.

In this application, the gas-containing concentrate is metered to the dryer through a feed line which is jacketed by a cooling pipe. The feed temperature is adjusted to be below the flash point when it enters the drying chamber. The nitrogen in the concentrate expands in the nozzle and the resulting foam issues as a thin, uniform blanket or film. The belt carries the foam through the drying zones where the moisture is removed, to an oscillating doctor blade that removes the dry product from the belt. The product drops into a chute, then to a screw conveyor which carries it to one of two receivers.

In order to reproduce the batch process on a continuous basis it was necessary to simulate the foam-forming function that was accomplished at the beginning of the batch drying cycle by the application of vacuum to the dryer (Fig. 3). A feed nozzle was designed that successfully fulfilled that function. The nozzle is a hollow right parallelepiped, whose front face is adjustable with shims to give the desired opening. The gas-containing concentrate enters the chamber where it begins to expand and continues to expand as it passes through the aperture as a thin, uniform blanket of foam.

MODIFYING PROCESS TO REDUCE COSTS

The work described above was a faithful translation of the batch process. An economic evaluation indicated that it, like the batch process, was too costly. The study further indicated that reduced costs could be obtained by reducing the bulkiness of the product as well as by increasing the dryer output, since packaging costs are lower for less bulky products (Claffey,

DEVELOPMENT of vacuum foam-dried whole milk

J.B., personal communication). Thus, research was begun to seek changes in the continuous process in the interest of economics that would have little or no effect on the product quality. The answer was found in a technique called "boil-down" (Schoppet et al., 1965).

It is a generally valid proposition that thinner films provide higher rates of heat and mass transfer, so a reduction in foam thickness appeared desirable. It had been found, however, that at 3 mm Hg absolute dryer pressure the thickness of the foam blanket reached a minimum at a nozzle opening of 0.047 in (Aceto et al., 1962) and that at smaller openings the foam blanket became thicker.

Thus, foam thickness could not be reduced further by manipulating the nozzle—it would be necessary to somehow destabilize the foam structure once it had been applied to the belt. This was accomplished by raising the pressure in the drying chamber from 3.0 to 19.0 mm Hg absolute. At 19 mm the foam structure partially broke down under the influence of heat ("boil-down"), leaving a thinner film. Figure 6 shows the stable foam obtained at 3mm Hg, and Figure 7 shows the semi-stable foam obtained at 19 mm Hg.

A comparison of the two techniques is given in Table 1. It can be seen here that the increased chamber pressure which caused the foam to be only partly stable, increased the output of the dryer by 43% and increased the density by almost two, thus leading to lower production and packaging costs. This was gained, moreover, with a slightly improved quality due, no doubt, to the decreased drying time.

Table 1—EFFECT OF DEGREE OF FOAMING on continuous drying and product characteristics of whole milk concentrate

	Stable foam	Semi-stable foam
Chamber pressure (mm Hg absolute)	3.0	19.0
Feed temperature (°F)	28	45
Feed rate (lb/min)	.40	.54
Gas content of concentrate (cc/liter)	120	205
Belt speed (ft/min)	9.3	15.9
Drying time (min)	2-1/4	1-1/3
Product rate (lb/hr)	10.7	15.3
Product moisture content (%)	3.5	4.1
Product bulk density (gm/ml)	0.22	0.40
Product solubility index (cc)	<0.25	<0.10
Product HMF content (micromols per liter)	0.85	0.70
Product flavor score	38.9	38.9

FOAM STABILITY PROBLEMS

Whereas the "boil-down" technique improved the economic picture, it brought problems. In the first place, research was needed to study the properties of concentrated whole milk foams and to find methods for characterizing their stability. An apparatus was developed for measuring two independent parameters—foaming ability and foam stability. Foaming ability was defined as the initial height of a foam immediately after its formation in a column developed for the test, and foam stability was defined as the rate at which the foam subsided.

It was found that the foaming ability of milk concentrates can only be described by a complex function of viscosity and temperature; that foaming ability reaches a minimum at about 70°F; and that the rate of foam subsidence can be described by an inverse exponential function of viscosity alone (Holden et al., 1964). The ratio of foaming ability to foam stability was found to be a measure of foam behavior that could be used as a parameter in later mathematical studies of the process (Craig et al., 1968; Craig et al., 1969).

OVERCOMING SEASONAL VARIATIONS

In addition to the complex response of milk concentrate foams to viscosity and temperature, it was observed that their behavior was also affected by a seasonal influence (Schoppet et al., 1965). In winter the foams were relatively unstable, in summer they were relatively stable, and in spring and fall they passed through transitional periods of stability. Such behavior was undesirable, for at the least extreme it would cause the process to be non-reproducible on a year-round basis, and at the most it would even cause the process to be unworkable during part of the year. Research was therefore necessary to either determine the cause and cure of this effect or to show how to compensate for it.

It was found that the concentrations of all the whey protein fractions except β-lactoglobulin varied with season in direct proportion to the foam stability. β-Lactoglobulin concentration had no seasonal trend (Della Monica et al., 1965b). It was further found that the phospholipid concentration of the milk also varied seasonally, being in inverse proportion to the foam stability (Holden et al., 1966). These results suggested that foam stability could be increased by adding whey proteins, or decreased by adding phospholipids. Since a relatively unstable foam was desired, work was directed to the addition of a phospholipid. Soy lecithin was the phospholipid chosen.

The simplest procedure for year-round plant operation would be to determine one concentration of lecithin to be added throughout the year. Since the naturally-occurring phospholipids of milk varied seasonally in concentration, one single, year-round concentration of lecithin would be possible only if the naturally-occurring variation in foam stability could be overridden. Earlier it has been found that foam stability was a function of viscosity (Holden et al., 1964). This fact was used to solve the dilemma—the natural phenomenon was overridden by increasing the viscosity through an increase in solids content of the concentrate to such a degree that the foam was stable all year round. Then uniform instability all year round could be accomplished by adding a single ratio of lecithin to milk solids.

OPTIMIZING THE DRYING PROCESS

With the solution of the foam stability problem attention was directed to optimizing the drying process. Thirteen independent variables were identified and seven dependent variables were originally selected to describe process efficiency and product quality. These variables are listed in Tables 2 and 3. The study was carried out over a three year period using experimen-

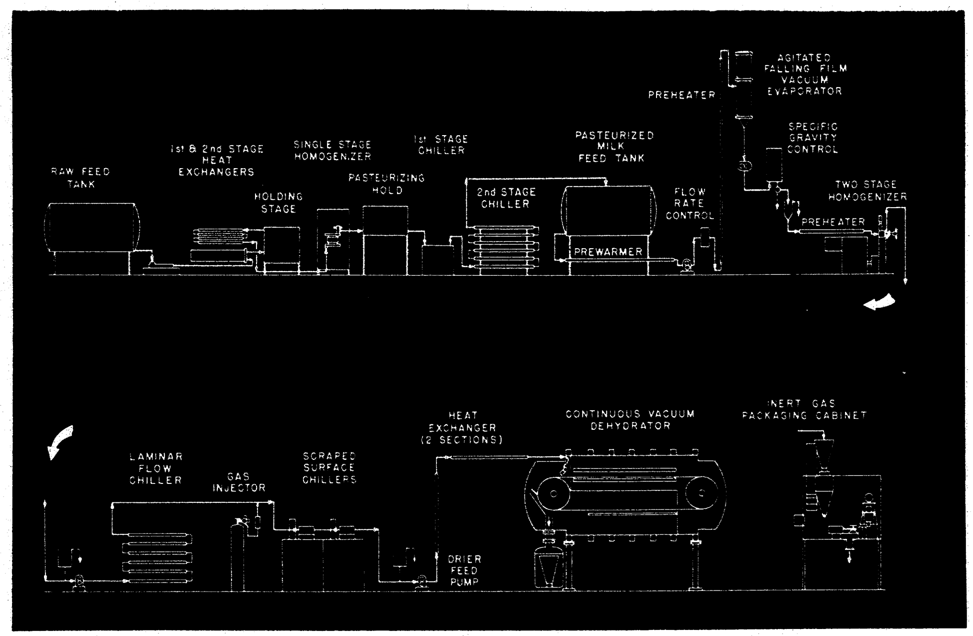

Fig. 8—**PILOT PLANT** *for vacuum foam-dried whole milk*

tal designs and mathematical model simulation. During the study only independent variable No. 8 was found insignificant over the range studied, and this was held constant during the rest of the study.

Prior to the study it was assumed that if moisture and HMF content were within acceptable limits the other dependent variables would be also. This proved to be largely correct (Craig et al., 1968; Craig et al., 1969). Although the study was terminated short of completion, a series of 42 runs based on the predictions of the study showed that it was essentially valid (Schoppet et al., 1970).

MARKET TESTING

The pilot plant as finally developed (Schoppet et al., 1970) is shown schematically in Figure 8. This pilot plant was used to produce a quantity of vacuum foam-dried whole milk sufficient to support a limited market study in the Lansdale, Pennsylvania area (Sills, 1970). The milk was packaged under nitrogen in cans containing the equivalent of one quart of fluid milk, labelled "Dairy Fresh," and sold from the dairy cases of nine supermarkets over a twelve week period. The milk was priced 4¢ below the store price of a quart of fluid milk. A cost estimate showed this to be reasonable (Turkot, V.A. personal communication). The product sold at a high rate per store for a new item, indicating a good potential for commercial success.

Overall, it was concluded that the product won high consumer acceptance. Purchasers reacted very favorably to the flavor, dispersibility, storage convenience, cost, and richness of the dry milk. A great majority of them considered it as good as or better than fresh whole milk on all factors (Sills, 1970).

An interesting finding was that the sales of "Dairy Fresh" seemed to have no effect on the sales of other dairy products. Apparently "Dairy Fresh" was purchased for special uses, thus finding an additional market for milk.

ECONOMIC FEASIBILITY

A complete economic evaluation was carried out on the product based on a plant containing two dryers, and three evaporating, homogenizing and gassing lines

Table 2—INDEPENDENT VARIABLES in optimization study

Independent variables	Units
1. Concentrate solids content	% (as—is)
2. Dryer feed concentrate gas content	cc gas/liter ungassed concentrate
3. Lecithin content	g lecithin/g solids
4. Belt loading	lb. conc./ft²
5. Chamber pressure	mm Hg absolute
6. Nozzle aperture	mm
7. Residence time (nozzle to cold drum)	min
8. Calrod temp, first zone, product side	°C
9. Hot drum temp	°C
10. Calrod temp, first zone, belt side	°C
11. Nozzle temp	°C
12. Fat content	% (MFB)
13. Foam time (seasonal parameter)	min

Table 3—DEPENDENT VARIABLES in optimization study

Dependent variables	Reference
1. Product rate	—
2. Product moisture content	a, b
3. Product HMF content	c, d
4. Product solubility index	a
5. Product dispersibility rate	e
6. Product bulk density	e
7. Product flavor	f

[a] American Dry Milk Institute, Inc. 1965
[b] Della Monica and Holden, 1968a
[c] Craig et al., 1961
[d] Della Monica et al., 1968b
[e] Sinnamon et al., 1957
[f] Aceto et al., 1966

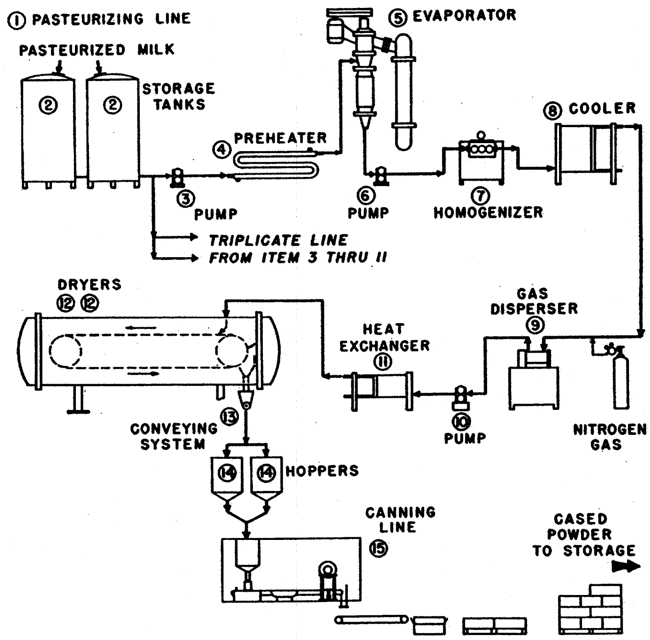

Fig. 9—**PROPOSED COMMERCIAL** *production plant for vacuum foam-dried whole milk*

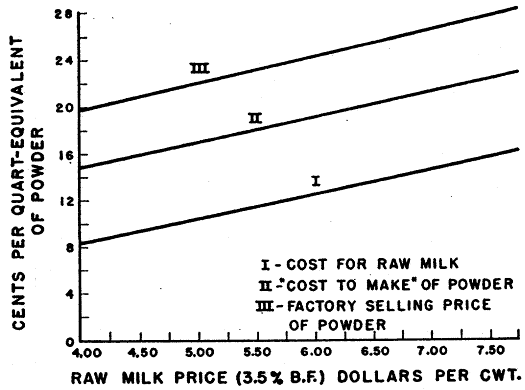

Fig. 10—**EFFECT OF RAW MILK PRICE** *on the commercial costs of vacuum foam-dried whole milk*

as shown in Figure 9. The plant would operate 24 hours per day, 250 days per year. The net input of raw milk after losses would be about 15,500 gallons per day and the output would be about 62,000 quart-equivalents per day. The powder would be packaged in No. 10 cans for the institutional market (Turkot et al., 1969).

This study showed that in 1968 the product could be produced and sold at 21¢ per equivalent quart in the institutional market. Figure 10 shows how the price paid for raw milk influences the selling price of the dry product.

A dry whole milk of desirable properties was developed as a result of this work. Furthermore, this product can be manufactured reproducibly the year round and sold at a profit. The sizes of the potential markets for this milk, both domestic and foreign, have not yet been well established, however. Nevertheless, the dairy and food processing industries have shown interest in this development. Its fate now depends on the needs and forces of the future.

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